

XR-3 TURN PERFORMANCE WHILE TOWING

Stewart Wayne Schreckengast



# NAVAL POSTGRADUATE SCHOOL

## Monterey, California



# THESIS

XR-3 TURN PERFORMANCE WHILE TOWING

by

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December, 1979

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XR-3 Turn Performance While Towing

by

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Lieutenant, United States Navy  
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Submitted in partial fulfillment of the  
requirements for the degree of

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## ABSTRACT

Results obtained on the XR-3 Testcraft verified the hypothesis that turn performance was not degraded while towing.

This investigation was experimental in nature, with emphasis on turn performance with respect to tow loads and testcraft velocity. A variable thrust, V-hulled vessel was towed behind the XR-3 and turn rate, velocity, and load cell drag was recorded.

Data is presented and compared for various turn rates, loads, and velocities. Recommendations are presented for further investigation.



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## I. INTRODUCTION

### A. BACKGROUND

A surface vessel which is supported partially by its own buoyancy, and partially by a captured pocket of air is referred to as an Air Cushion Vehicle (ACV). One of the earliest records of an ACV was one devised by the Swedish scientist and philosopher Swedenborg, who in 1716 demonstrated a model which was operated by pedal-driven pumps. However, the idea did not receive further attention until the late nineteenth century when steam power became available. True scientific investigation of air cushion vehicles began in the mid-1950's when efficient and light-weight propulsion devices became affordable (Ref. 1).

With an ever increasing requirement for a mobile and rapidly deployable military force, the concept of air cushion vehicles has been evaluated by the Navy for several operational systems.

An ACV developed strictly for over water use is known as a Surface Effect Ship (SES). ACV's are generally divided into two categories, the Captured Air Bubble (CAB), and the Hovercraft.

A CAB vehicle uses flexible bow and stern seals which ride on the surface, and solid side walls which extend below the surface, Fig. 1. Thus, a bubble of air is captured and the majority of the vessel is elevated above the water surface. At cruise speed the CAB can override its bow and stern seal



wakes and greatly reduce its hydrodynamic drag. This is referred to as "going over the hump". It is very similar to the drag rise experienced by a supersonic airfoil as it passes through Mach 1, the speed of sound. Once the CAB vehicle is over the hump it operates on a cushion of air whose frictional drag is more than 800 times less than its drag when in water contact. Thus, much greater velocities can be achieved with only a slight increase in thrust (Ref. 2).

Hovercraft vessels use a completely flexible perimeter which rides above the surface due to venting of its cushion overpressure. This venting produces an aerostatic lift and forms a ground cushion much like that developed under a helicopter.

Therefore, CAB's require only a small amount of power to remain on cushion, but the sidewalls and seals develop surface friction. Hovercraft have no hydrodynamic friction, but require more power to equalize the cushion losses due to venting (Ref. 3).

As documented by the National Science Foundation in Ref.

4:

"In the weight range of 30 to 300 tons and in the speed range of 45 knots where hydrofoil craft, ACV and planing craft are currently competing, the former two vehicles have distinctly better performance than any other type except airships. However, if size is further increased, with or without a weight increase, ACV will gain a distinct advantage over hydrofoil crafts in terms of maximum L/D ratio." Figure 2.



It is for these reasons that ACV development is so important to future naval strategy.

#### B. XR-3 TESTCRAFT

The XR-3 is a captured air bubble surface effect ship. In 1965 it was constructed by the David Taylor Model Basin, now designated the David Taylor Ships Research and Development Center (DTNSRDC). The XR-3 is 24½ feet long, 12 feet wide and weighs about 6,090 pounds, Fig. 3. There are two 55 horsepower Chrysler outboard motors mounted on the stern of the testcraft for propulsion and steering. The air bubble cavity, or plenum chamber, and the seals are pressurized by five blower-fans with their own internal combustion engines. Pressure can be varied in the seals and plenum independently.

In 1967 the XR-3 was modified by DTNSRDC and transferred to the Aerojet-General Corporation in San Diego for continued testing. The supervising authority for these tests was the Joint Surface Effect Ships Project Office, now the Surface Effect Ships Project Office (SESP0) of the Naval Sea Systems Command (Ref. 5).

Early in 1970 the CR-3 was transferred to its current home at the Naval Postgraduate School in Monterey, California for continued investigation of basic and advanced SES technology. This research is under Statement of Work directives of the SESP0. From June, 1972 until April, 1973 the XR-3 was extensively modified and an updated data acquisition system was installed (Ref. 6). At this same time the bow



and stern seals were replaced with more flexible seals which provided improved performance. Figure 4 shows a typical drag versus velocity curve for the XR-3 (Ref. 7). As thrust is applied, the testcraft accelerates from rest and a wake begins to form in front of its bow and stern seals. At point #1, the stern seal overrides its wake and the state of "secondary hump" is reached, drag is reduced, and the craft quickly accelerates through point #2 to point #3. Figure 5 shows the momentary venting of the sidewalls while the stern wake is being overridden. At point #3, Fig. 6, "primary hump" is reached, the bow wake is overrun, and the craft is "on cushion". Figures 7 and 8 show the testcraft "on cushion" with no bow wake. Thus, the XR-3 accelerates from a velocity of about 8 knots (below secondary hump) to a velocity of about 18 knots (on cushion) with no increase in thrust.

All testing of the XR-3 is conducted by the Naval Postgraduate School on Lake San Antonio, 100 miles south of Monterey.

## II. NATURE OF THE PROBLEM

In May of 1976, Deputy Secretary of Defense, William P. Clements, Jr., sent a memorandum to the Secretary of Defense, William Middendorf, which stated:

"I have determined that we should proceed to design, construct and test a prototype SES of approximately 3000 tons design gross weight. This is to serve as a combined technology prototype and operational practicality prototype for a possible frigate-size operational SES."



According to Ref. 3, this craft was scheduled to complete sea testing in the mid-1980's.

Many current naval projects require a vessel to tow an object or an array of devices. The submarine Deep Submergence Rescue Vehicle (DSRV), for example, has a weight of about 2 percent of the proposed 3000 ton SES (3KSES). Admiral Cagle states in Ref. 1 that "shipbuilders consider that the practical speed limit of the traditional hulled ship is about 35 to 40 knots". The DSRV could be moved to a rescue site on-board a SES at a speed of three to four times that of a conventional transport ship, Fig. 9, and then be maneuvered with ease by using the SES's variable-direction vectored-thrust waterjet nozzles (Ref. 8). The 80 to 100 knot speed of the SES would allow this type of platform to launch and recover aircraft independently of surface winds, and it could outrun any submarine threat. Its shallow draft of 14 feet greatly reduces its susceptibility to torpedo attacks. Admiral Cagle also commented that "the next naval field which will feel the impact of the ACV is mine warfare. An ACV operating over the surface of the sea makes only the smallest acoustic, magnetic and pressure signature. Moreover, the ACV has promise of being useful as a minesweeper."

An additional safety feature is built into the SES. Unlike current aircraft carriers and transport ships which may take several miles to come to an emergency stop, the cavity pressure of the SES can be vented and the waterjet propulsion



nozzles reversed to bring the craft to a full stop within 3 or 4 boat lengths, according to Ref. 3.

The purpose of this investigation was to evaluate the performance characteristics of the XR-3 while towing, and to determine the effect of tow loads on turn rate and velocity.

### III. EXPERIMENTAL PROCEDURES

The XR-3 was launched for each test run at Lake San Antonio with its center of gravity at the optimum position of 119 inches forward of the stern (Ref. 9). As noted in Ref. 10, the plenum pressure is variable, but due to the narrow velocity band investigated in this report, the plenum pressure was held constant.

Initial towing investigation was accomplished by connecting the bow of a V-hulled boat to the center stern of the XR-3 with a 110 feet tow line. The tow connection point on the XR-3 is at its vertical and lateral center of gravity. Therefore, the pitch and the roll of the XR-3 was unchanged while towing, and only the yaw and drag were affected. Towing at various speeds without turning was studied, followed by both left and right turns at several turn rates. It was beneficial to have a powered tow load because the V-hulled boat's thrust could readily be varied to allow rapid load variation. For this reason the V-hulled boat was also used as the tow load for later quantitative testing. It was interesting to note that in turns the V-hull of the boat kept it



centered between the wakes of the XR-3's engines. In sharp turns as the boat neared the inside wake, the wake rode up on the hull, causing it to roll and yaw away from the wake and back toward the center of the calm water aft of the XR-3. Once it was centered in the calm area the tow line tightened and pulled the bow of the boat in line with the path of the XR-3. Personnel onboard the towed boat stated that almost no rudder input was required to maintain position due to the natural correcting actions of the wake and tow line.

These procedures worked very well once the XR-3 was on cushion; however, there was insufficient thrust to pass the XR-3 through Secondary Hump while the full drag of the towed boat was attached. For this reason all runs were initiated from on-cushion with minimum tow drag. The thrust of the towed boat was then reduced until the desired tow drag was added.

After initial testing was completed, a load cell was attached to the towed boat end of the tow line and tow loads were broadcast to the XR-3 on ship-to-ship radio. After several runs in this configuration it was established that the readings on the load cell were exactly the same as the increase in drag measured on the seal load cells of the XR-3, Fig. 10. Therefore, the quantitative runs were made without a tow line load cell and drag was recorded by the onboard data acquisition system.

A fourteen channel Pemco Model 120-B magnetic tape recorder was used to make a permanent record of data measured



onboard the XR-3. The system was calibrated in accordance with procedures in Ref. 6. The edge track channel was used for operator voice comments to aid in synchronizing automatic data collection with manually recorded data to assure the accuracy of the recorded data. The other channels were used to record information from seal load cells and internal gyro-systems. Available sensor installations are shown in Fig. 11. Once a run was completed, the tape recording was fed into a signal conditioning unit, Fig. 12, with built-in analog-to-digital conversion and strip chart recorder output (Ref. 11). During the analysis of test run data it was determined that dynamic error was small, allowing observed readings to be plotted directly without modification.

#### IV. PRESENTATION OF DATA

Data gathered during the series of test runs has been tabulated as well as graphically plotted.

##### A. TURN RATE VERSUS TOW LOAD

A series of runs was made with indicated drags from just above 400 pounds to almost 700 pounds. A complete investigation of both left and right turns is presented in Figs. 13 through 24.

##### B. TURN RATE VERSUS VELOCITY

Variations in turn rate and velocity are presented for left turns in Fig. 25 and for right turns in Fig. 26.



### C. TURN RATE - LOAD ENVELOPE

A composite operating envelope, much like the velocity-load ( $V_n$ ) diagram of an aircraft is presented in Fig. 27.

## V. CONCLUSIONS AND RECOMMENDATIONS

The results and conclusions of the investigation were based on the data obtained by Naval Postgraduate School personnel between January, 1979 and September, 1979.

Tests for this investigation were conducted in nearly calm, fresh water. Since this study was restricted to the XR-3 testcraft, the performance parameters of length-to-beam ratio, propulsion mode variation, and sidewall geometry were not investigated. Also, the variable of tow loads such as a submerged tow, or a flat-hulled surface tow or tow line length were not studied.

The composite turn rate versus drag load diagrams, Figs. 15 and 20, show that the testcraft accelerates to a velocity of about 21 knots with no turn rate or tow load. Under these conditions the drag reading is about 550 pounds. As the tow load is added the velocity decreases to about 18 knots and the drag increases to nearly 700 pounds. When a turn is initiated the velocity decreases at a rate just less than 1 knot per 2 degrees-per-second turn rate. When the tow load was reduced by increasing the towed boat's thrust, both the turn rate and velocity increased. As stated by Edwards in Ref. 12, the velocity of the testcraft not under tow between



the speeds of 18 to 21 knots was decreased by  $\frac{1}{2}$  knot per degree-per-second of turn rate. Therefore, tow loads in the range of 2% of the XR-3 gross weight do not appear to degrade its turn performance. However, turns to the left appear to hold their velocity better than to the right. This is due to the right propeller tending to cavitate more in turns to the right. Figures 25 and 26 clearly show the decrease in velocity with increased turn rate. Note how the turn rate and velocity both increase in a turn when the tow is removed. The Turn Envelope, Fig. 27, shows the area of investigation in this study with various towing conditions and velocities pointed out. As shown in Fig. 28, it is believed that the tow load helps reduce the skidding action of the XR-3 in turns, and this reduces the side loads and friction on the sidewalls, allowing more thrust for turn performance.

#### A. CONCLUSIONS

1. Towing a moderate weight surface device behind the XR-3 testcraft did not degrade its turn performance.
2. The towed device helps to prevent the XR-3 from skidding in turns, thus increasing the thrust available for propulsion.
3. A 25% increase in seal drag, while towing, produces only a 15% decrease in velocity.
4. Sufficient XR-3 thrust was not available to reach the "on cushion" condition from rest while towing.



## B. RECOMMENDATIONS

1. The XR-3 should be tested under tow using both submerged and flat-hulled surface loads.

2. Optimization studies should be conducted to determine appropriate tow line lengths for each tow mission.



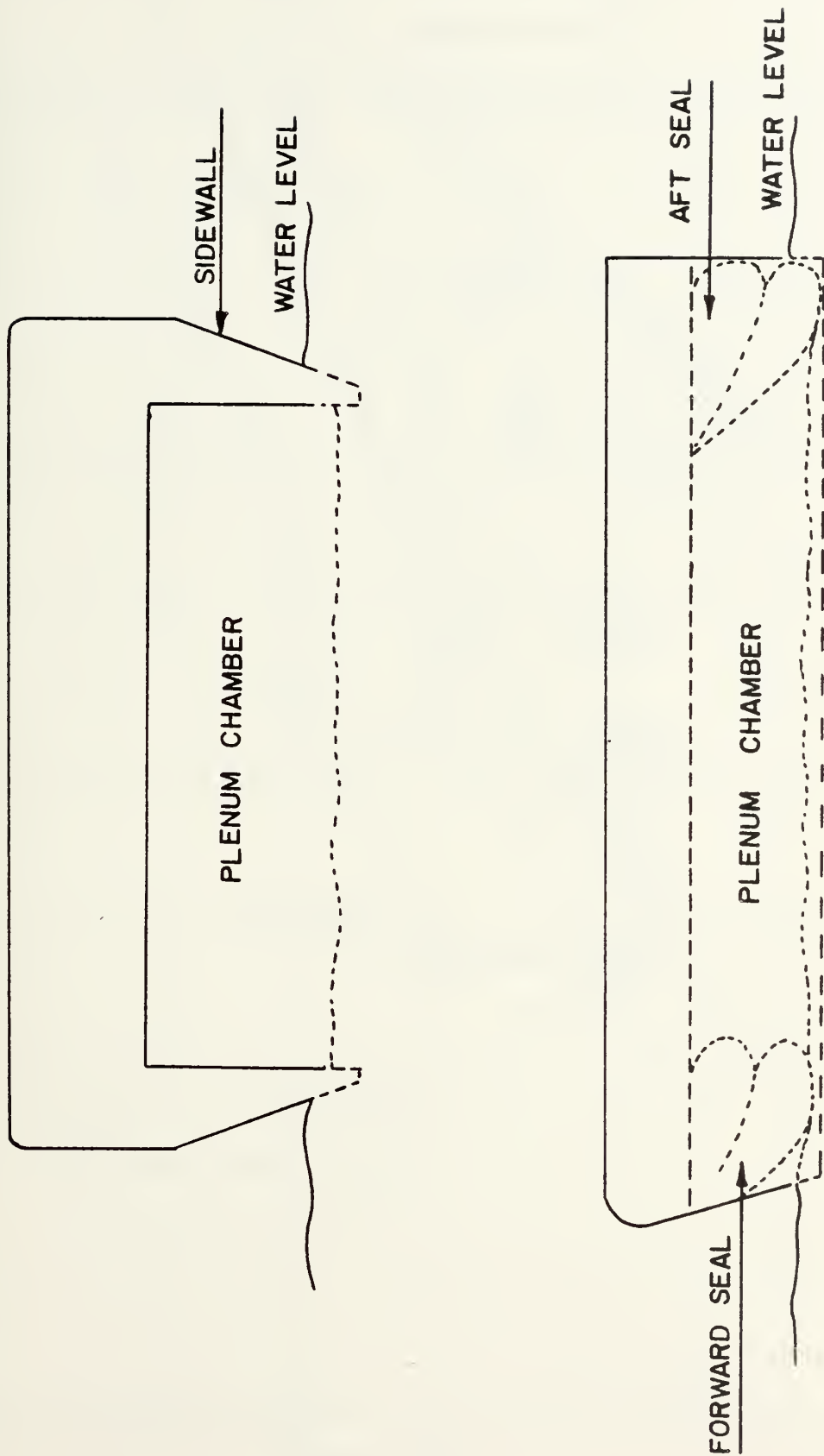


FIGURE 1. CAPTURED AIR BUBBLE VEHICLE



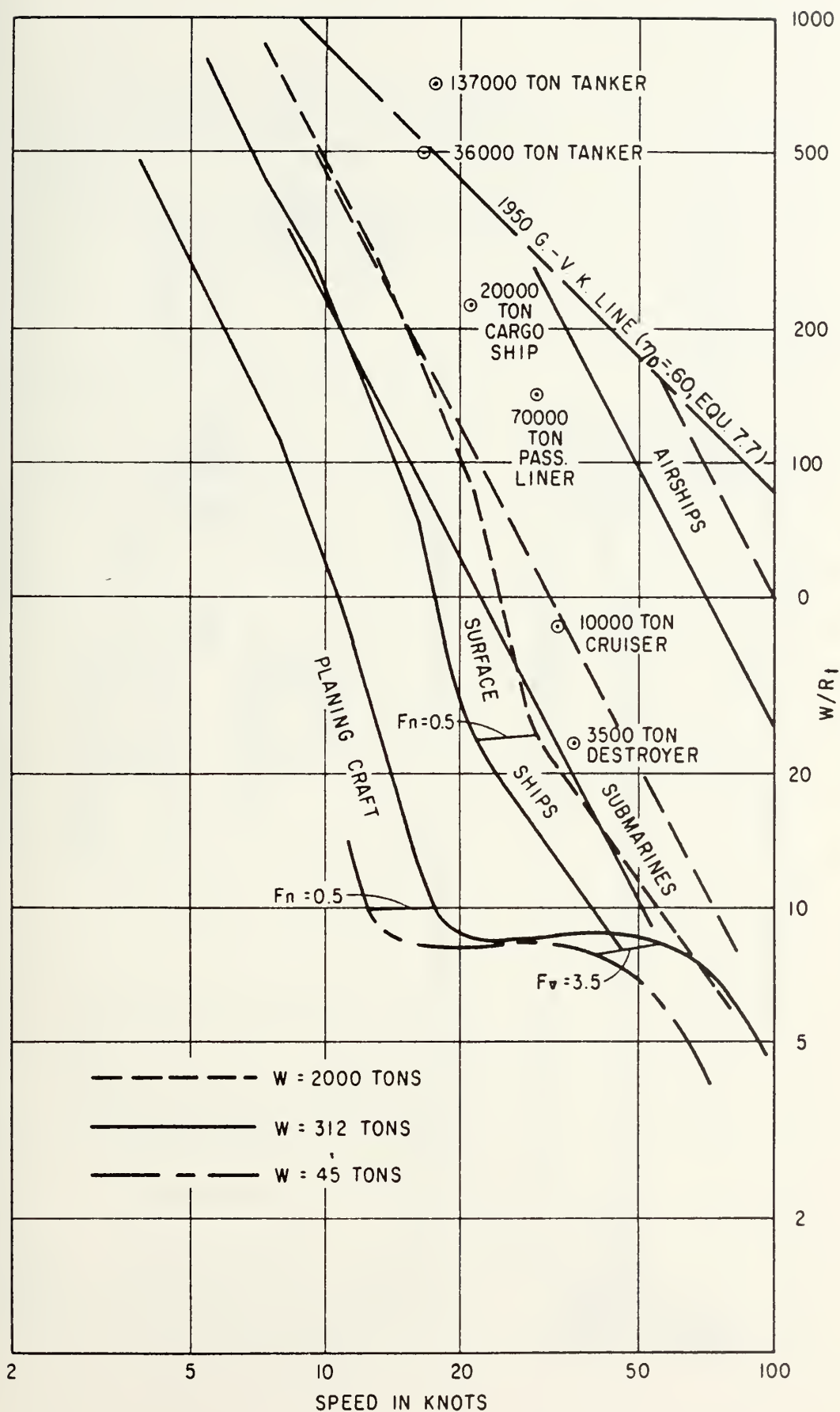


FIGURE 2. LIFT/DRAG RATIO OF VEHICLES



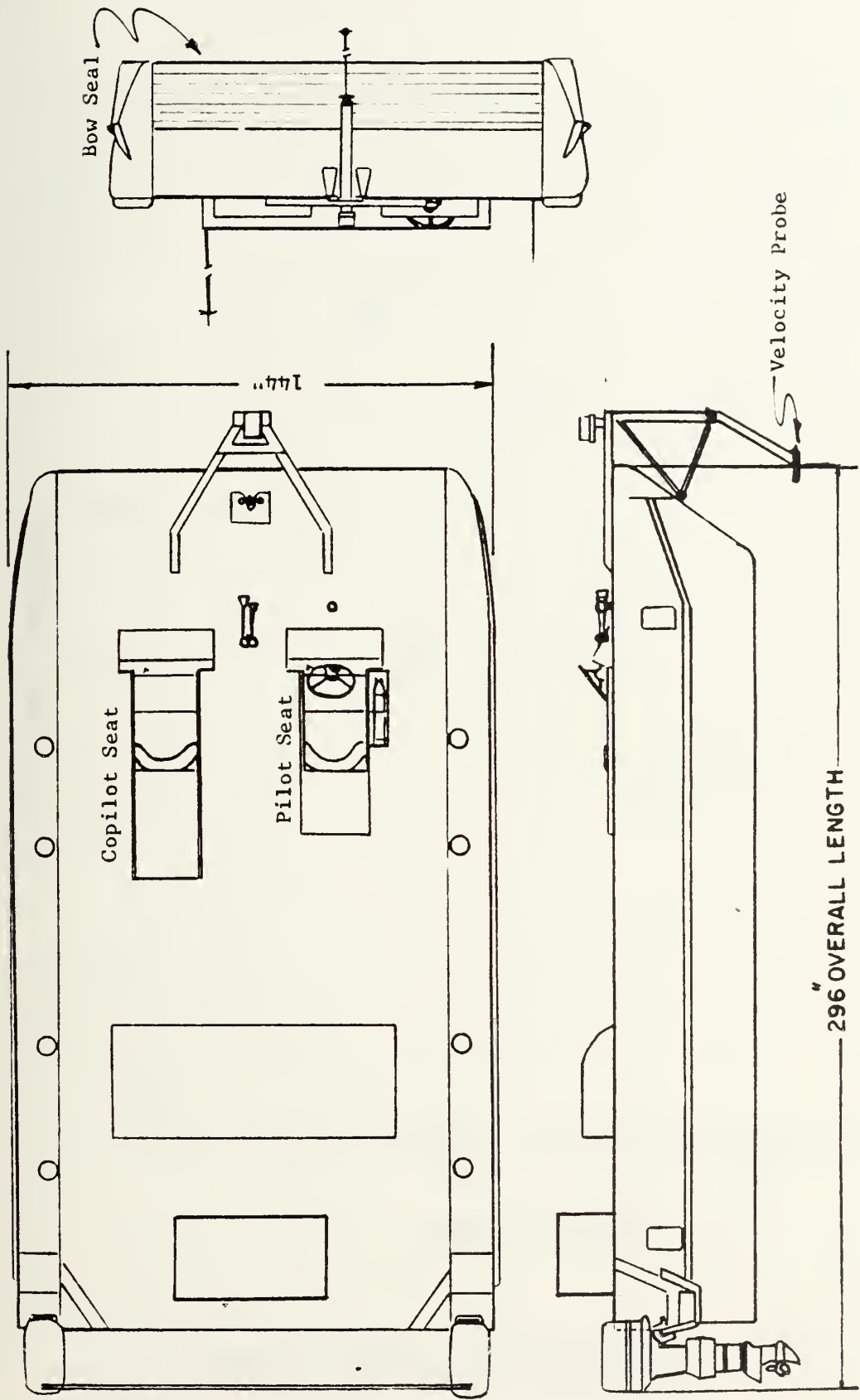


FIGURE 3. XR-3 TESTCRAFT



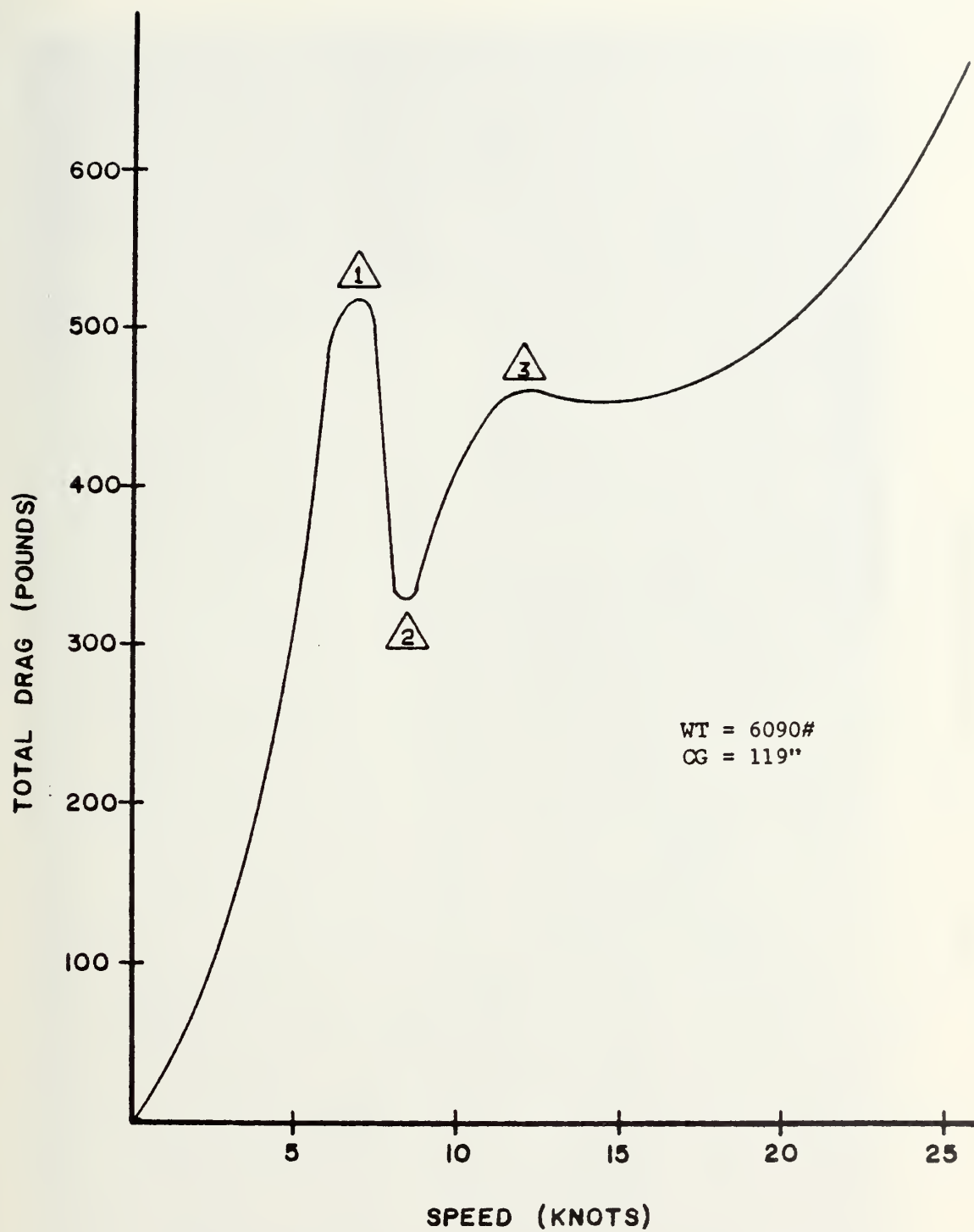


FIGURE 4. TESTCRAFT DRAG VERSUS SPEED



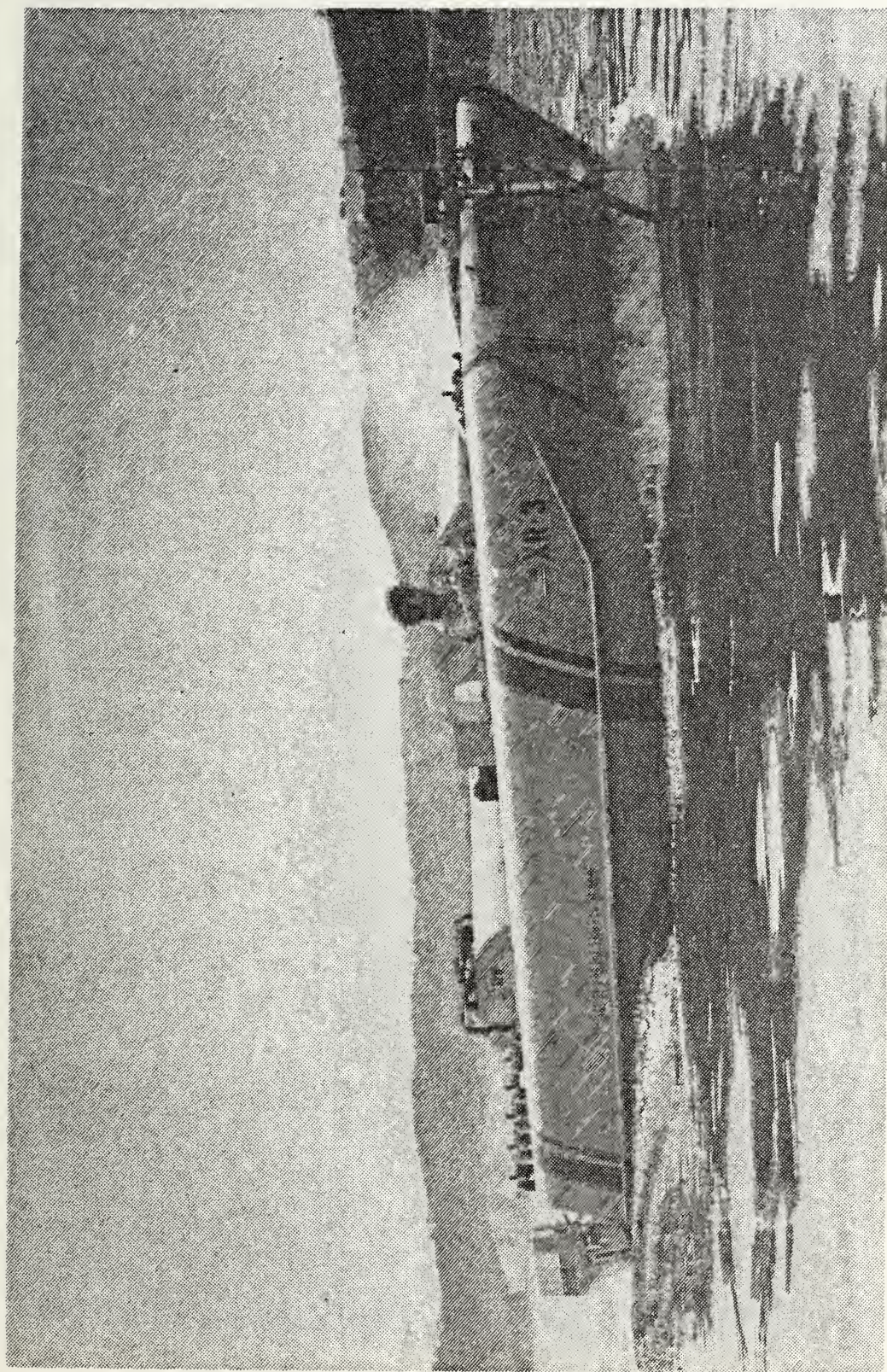


FIGURE 5. XR-3 BELOW SECONDARY JUMP



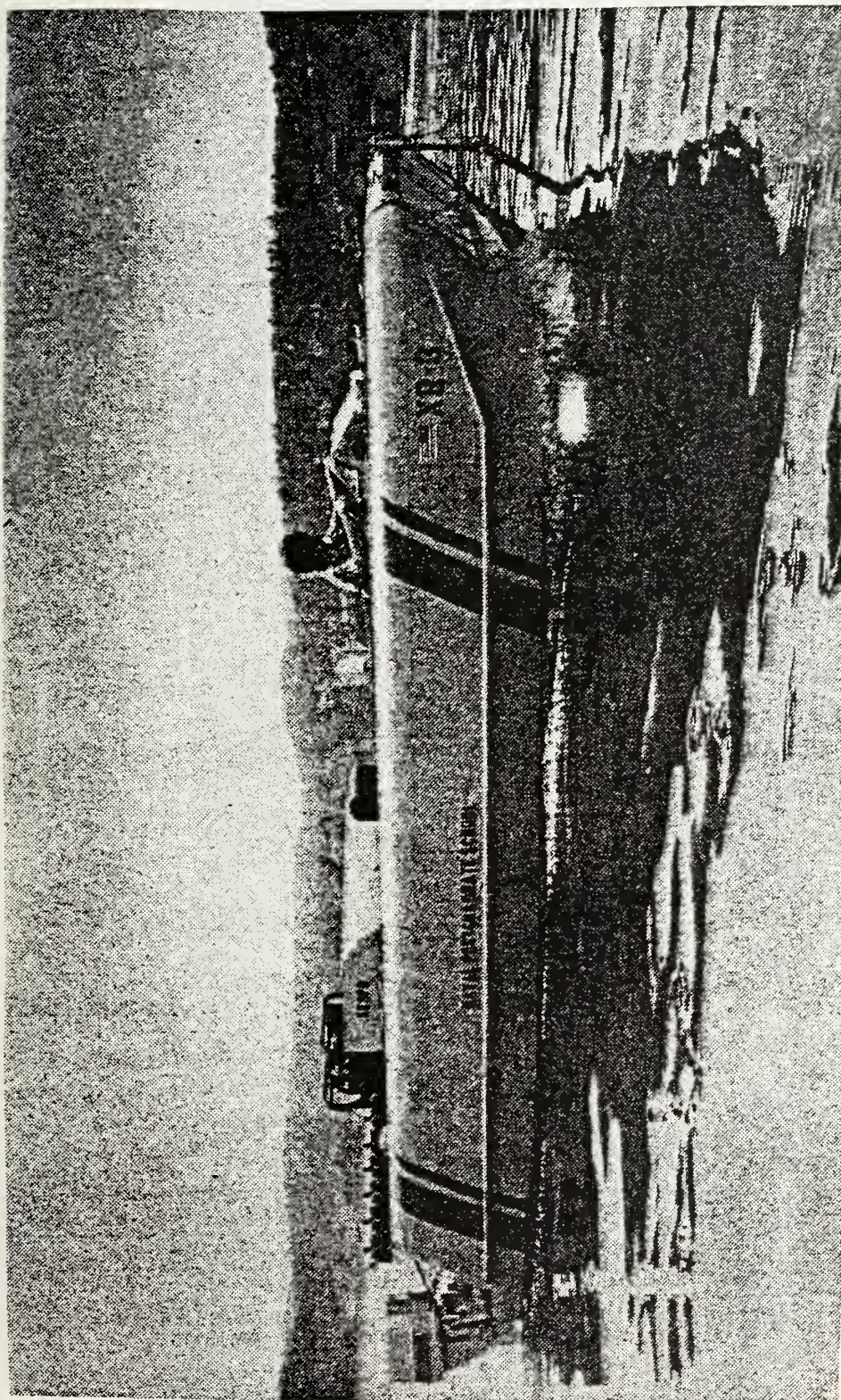


FIGURE 6. XR-3 BETWEEN SECONDARY AND PRIMARY JUMP



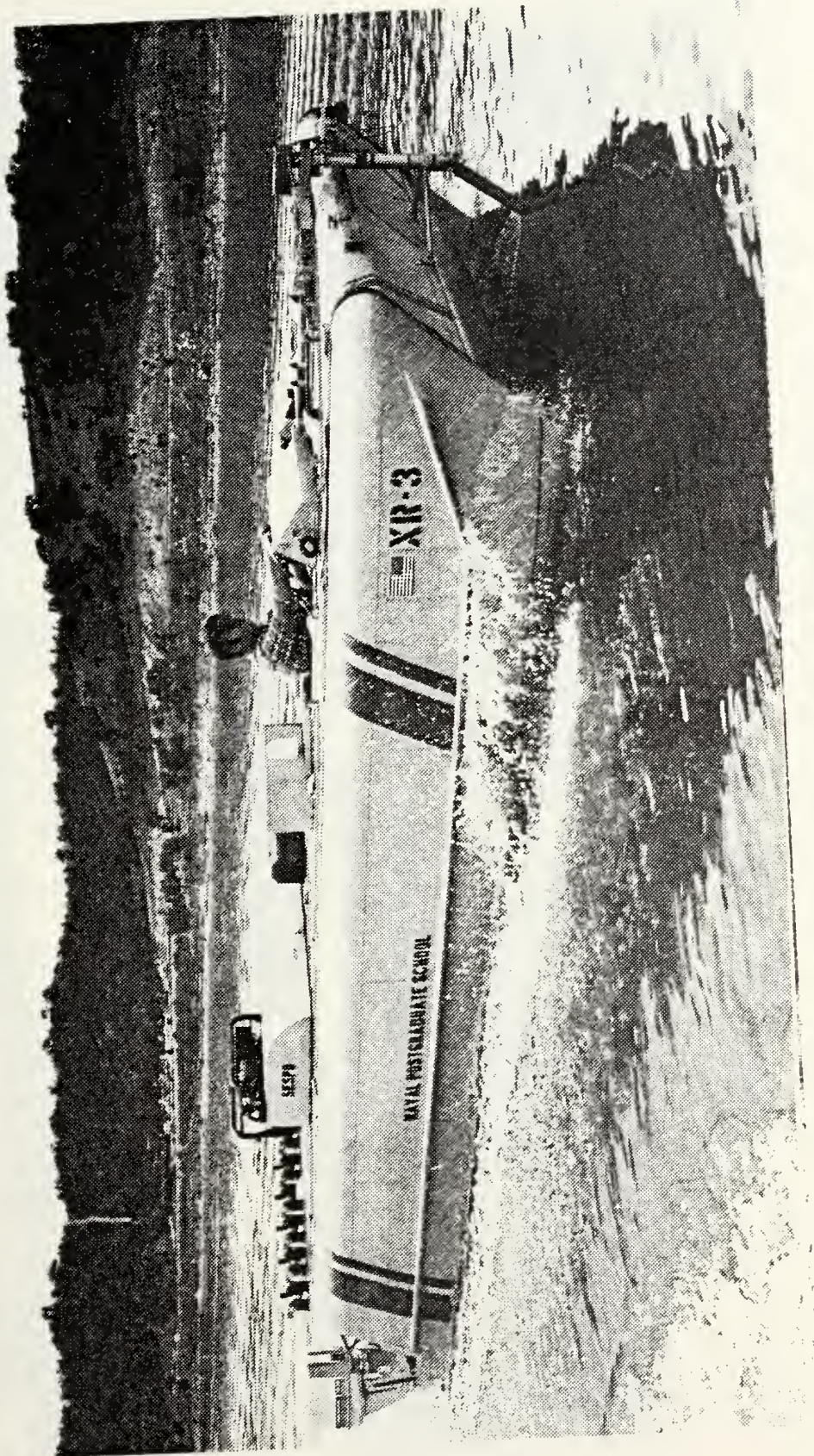


FIGURE 7. XR-3 Post Hump - Bow View





FIGURE 8. XR-3 Post Hump - STERN VIEW



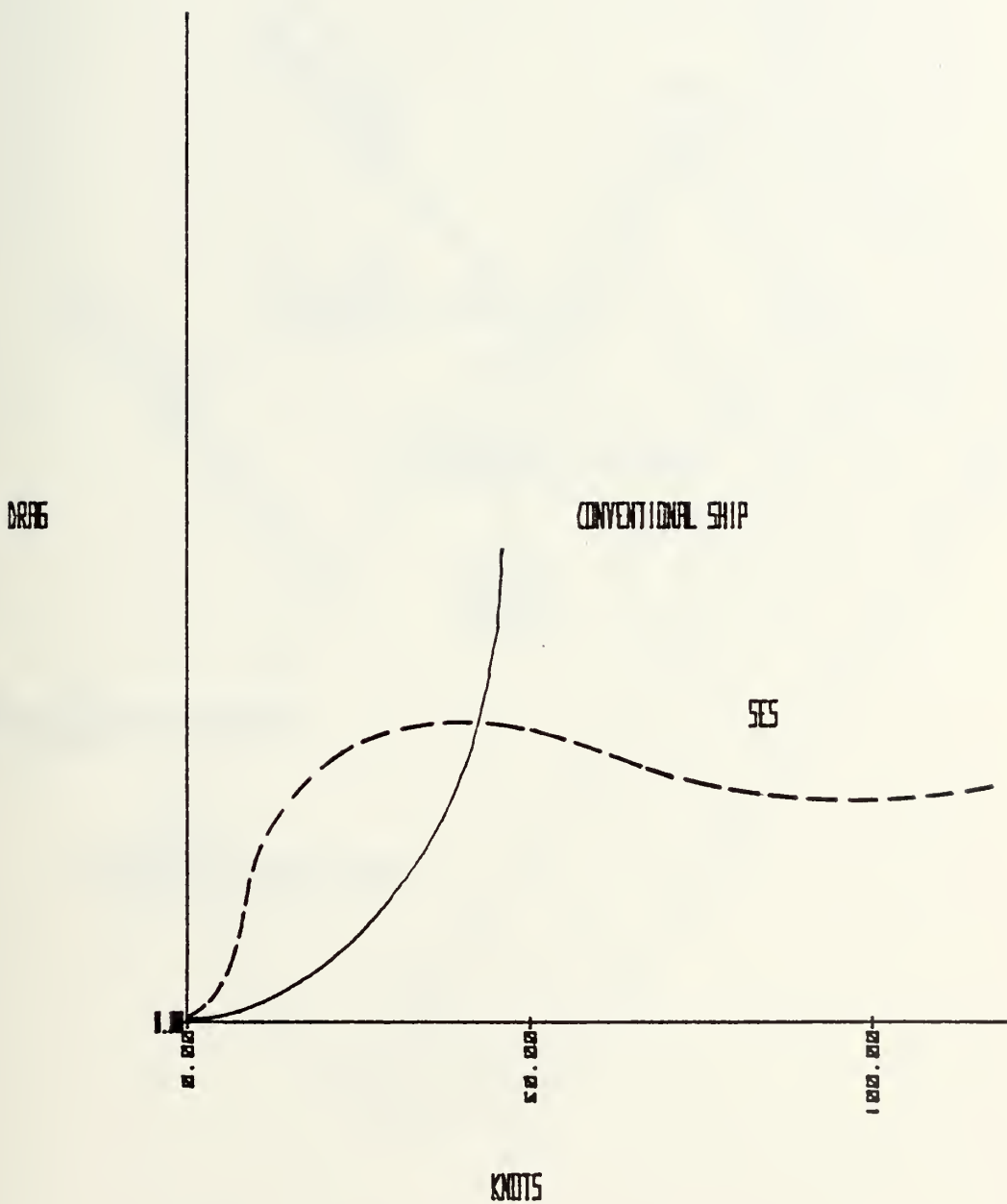


FIGURE 9. SHIP VERSUS SES DRAG-VELOCITY CURVES



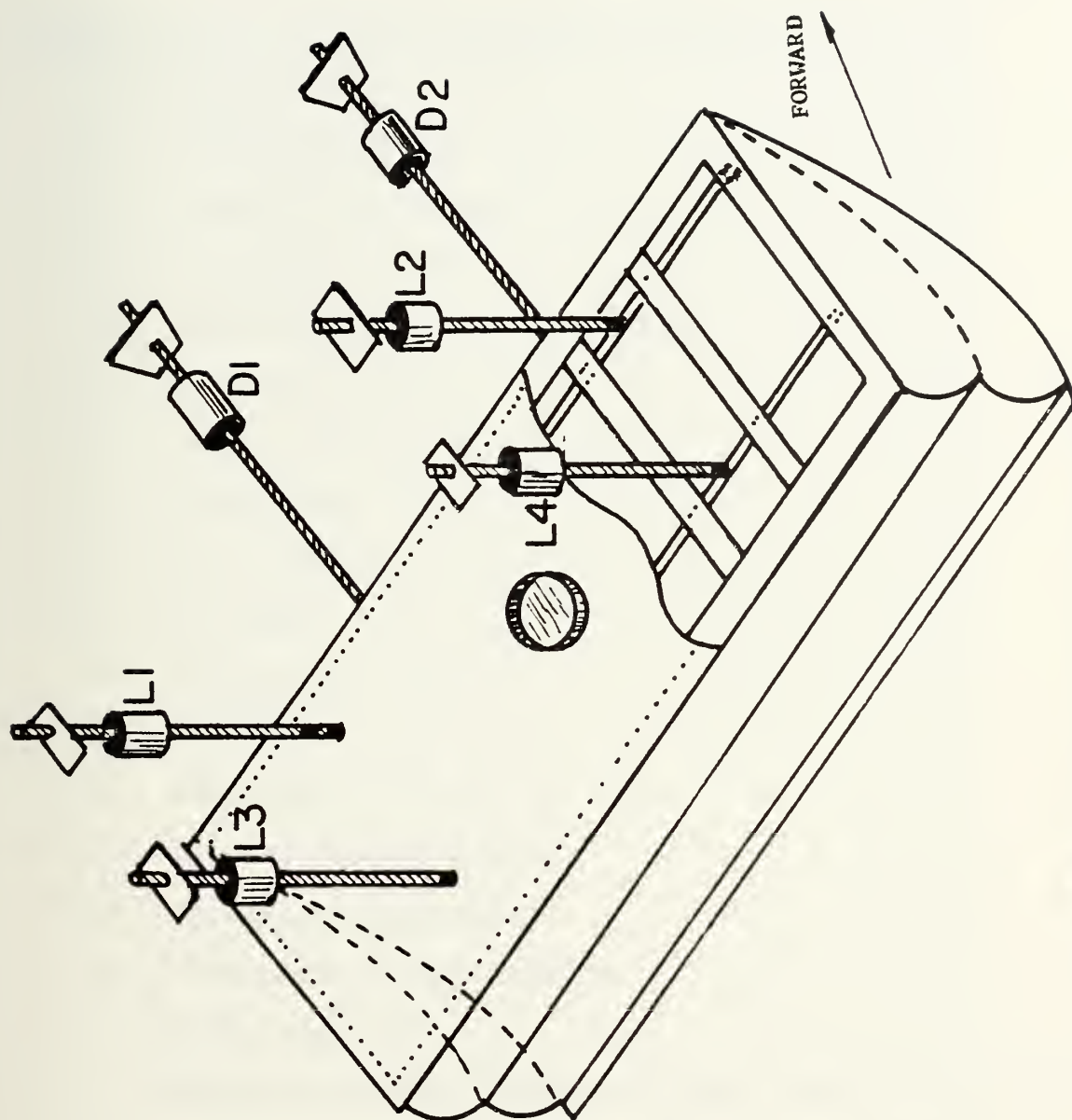


FIGURE 10. SEAL LIFT (L) AND DRAG (D) LOAD CELLS



## SENSOR ASSIGNMENT

The following sensors are installed on the XR-3 as a basic part of its Data Acquisition System:

1. Port Thrust
2. Starboard Thrust
3. Forward Seal Pressure
4. Aft Seal Pressure
5. Plenum Pressure (two positions)
6. Testcraft Velocity
7. Water Immersion Height
8. Pitch Angle
9. Roll Angle
10. Yaw Angle
11. Pitch Rate
12. Roll Rate
13. Yaw Rate
14. Lateral Acceleration
15. Vertical Acceleration
16. Longitudinal Acceleration
17. Rudder Position

A combination of any thirteen of these inputs can be recorded on the fourteen channel recorder (one channel is reserved for voice inputs).

Figure 11. XR-3 SENSOR ASSIGNMENT



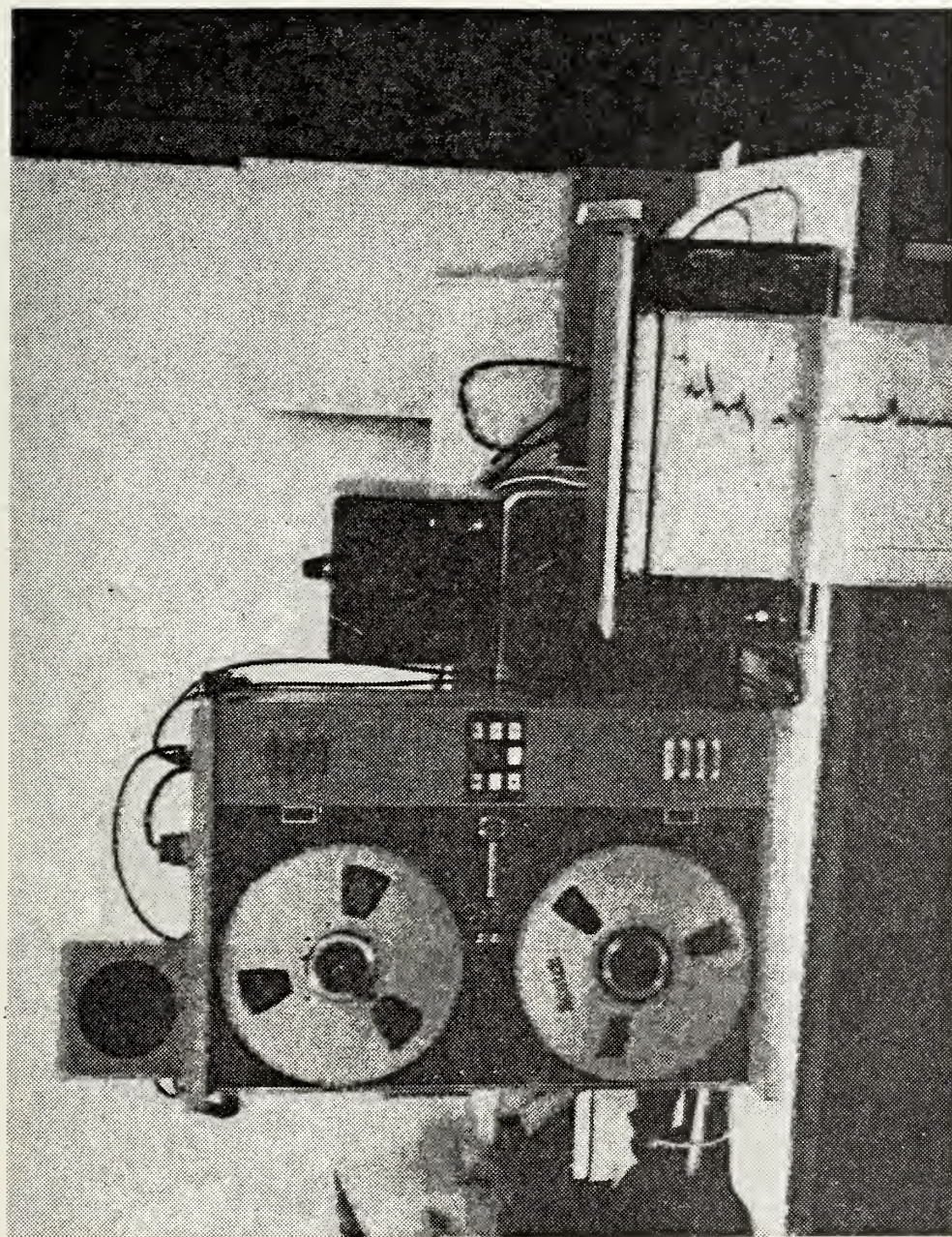


FIGURE 12. XR-3 SIGNAL CONDITIONING UNIT



TURN RATE versus LOAD DATA, RUN A

Run Number	Tow	Turn Rate (deg/sec)	Direction	Load (lbs)	Velocity (knots)
1.	no	0		580	19
2.	yes	0		615	18
3.	yes	2.0	left	620	17.5
4.	yes	4.0	left	625	17
5.	no	4.4	left	560	20
6.	no	0		550	20.5
7.	yes	0		600	18
8.	yes	4.3	left	605	17.5
9.	no	4.5	left	595	18
10.	no	0		535	21
11.	yes	0		595	18
12.	yes	4.3	right	590	17
13.	no	6.0	right	530	19
14.	no	0		550	20
15.	yes	0		580	18
16.	yes	8.6	right	550	16
17.	no	10.0	right	520	17

FIGURE 13. TURN RATE VERSUS LOAD DATA, RUN A



TURN RATE versus LOAD DATA, RUN B

Run Number	Tow	Turn Rate (deg/sec)	Direction	Load (lbs)	Velocity (knots)
1.	no	0		425	19
2.	yes	0		600	18
3.	yes	2.9	right	610	17
4.	yes	4.7	right	600	16
5.	no	6.3	right	540	17
6.	no	0		540	20
7.	yes	0		616	19
8.	yes	3.9	left	619	18
9.	no	4.7	left	550	18
10.	no	0		455	19
11.	yes	0		650	18
12.	yes	5.0	right	620	16
13.	no	6.0	right	520	18
14.	no	0		525	19
15.	yes	4.0	left	630	18
16.	no	4.9	left	550	18

FIGURE 14. TURN RATE VERSUS LOAD DATA, RUN B



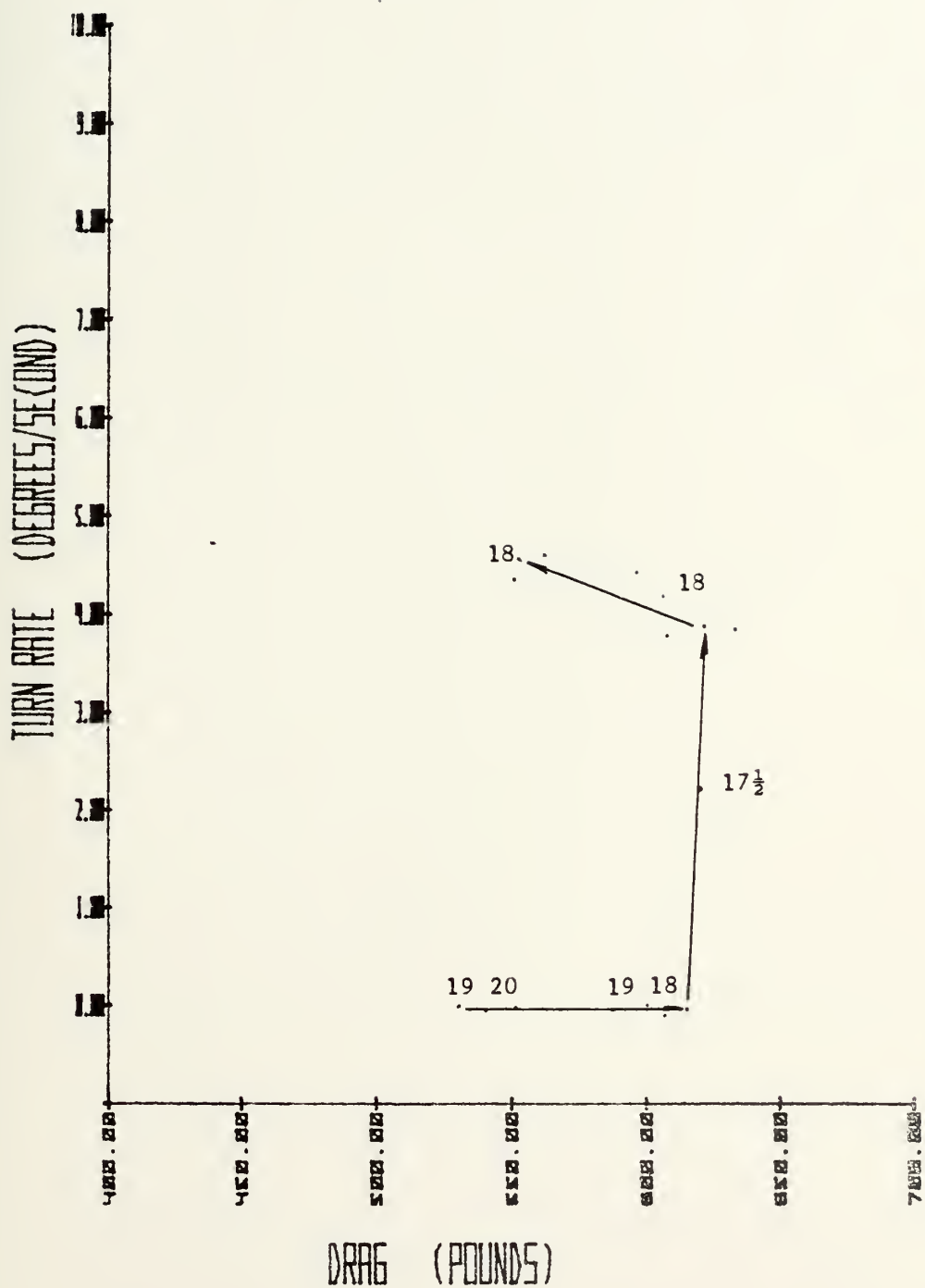


FIGURE 15, COMPOSITE LEFT TURN PERFORMANCE



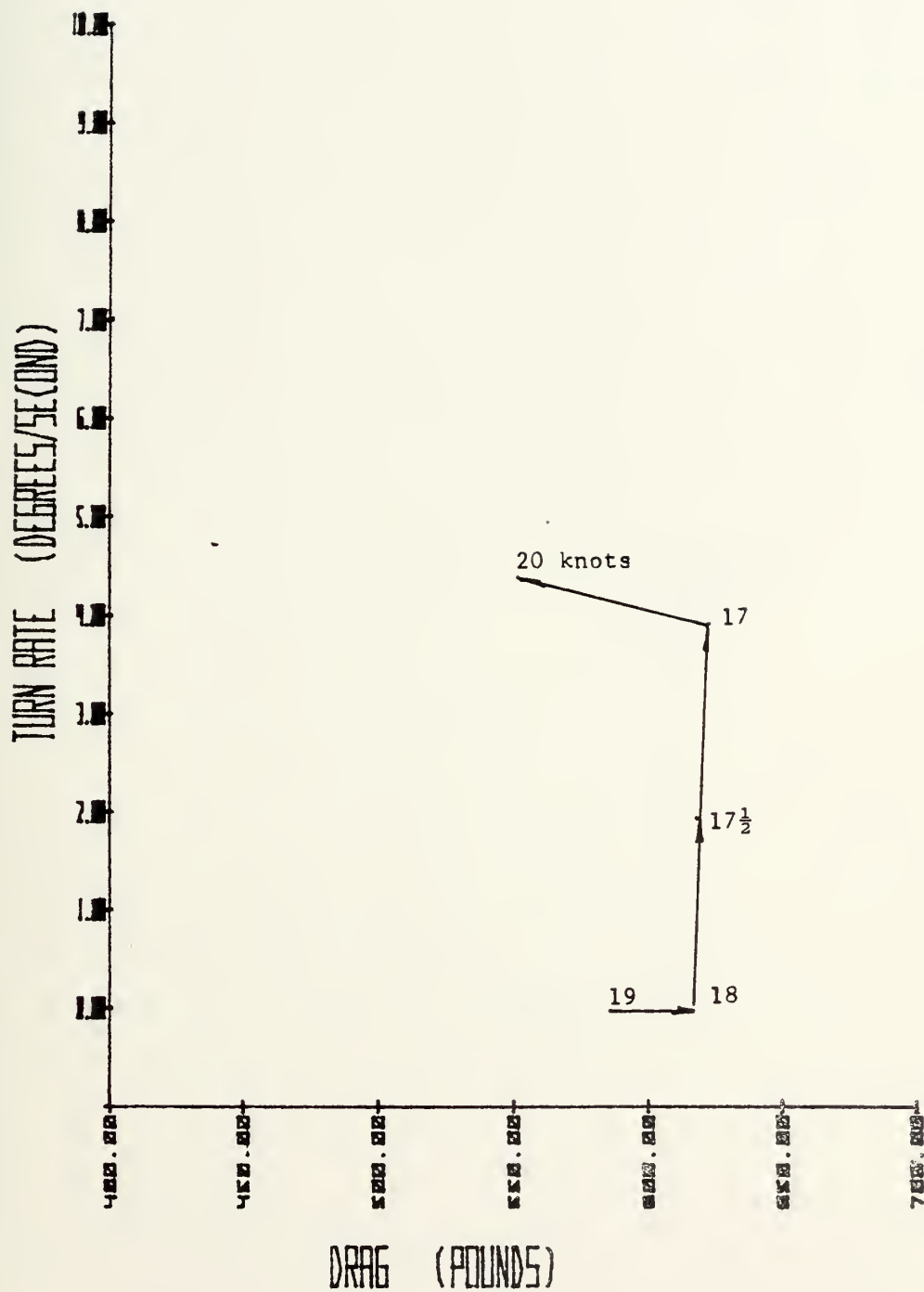


FIGURE 16. LEFT TURN RUNS A 1-5



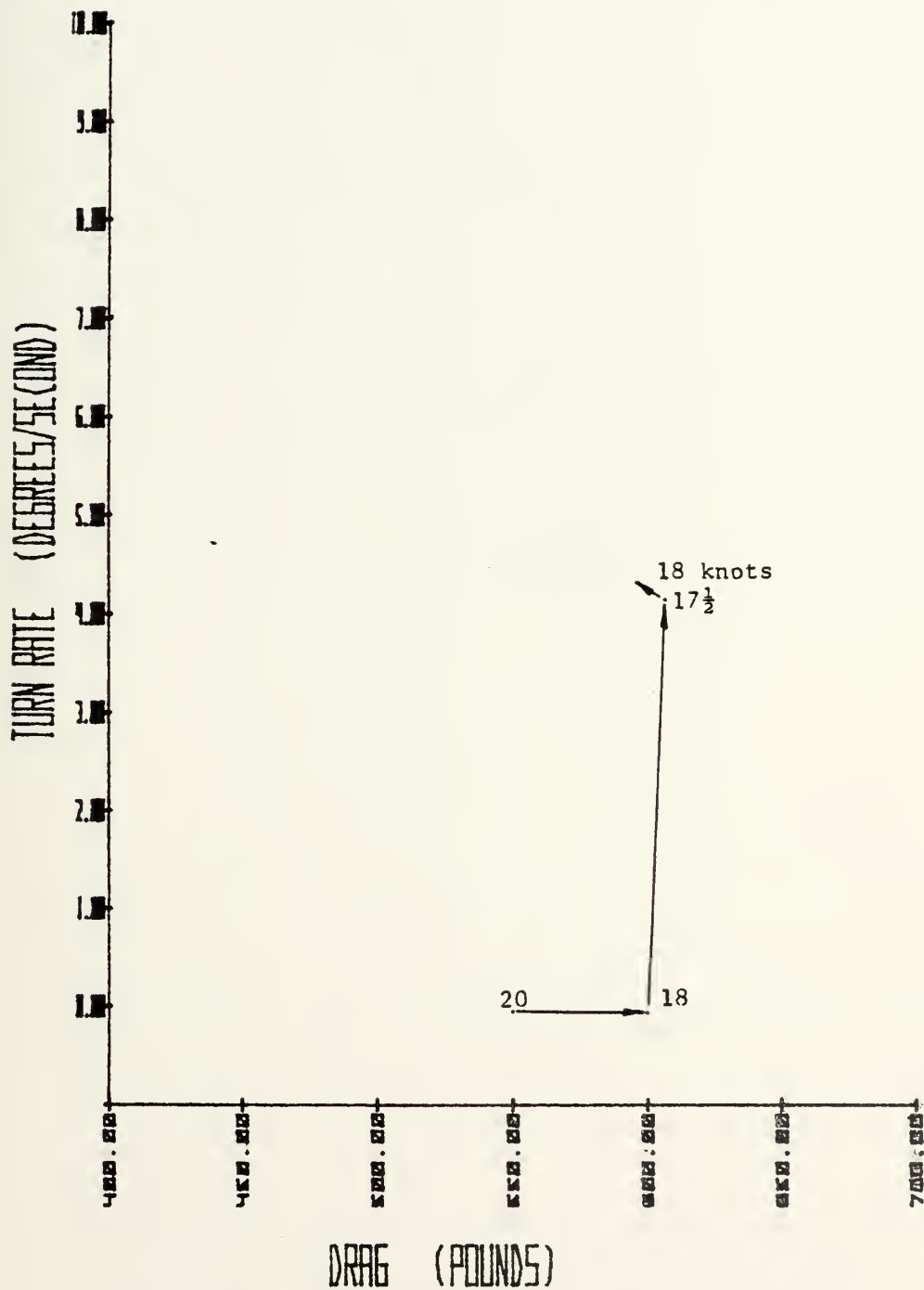


FIGURE 17. LEFT TURN RUNS A 6-9



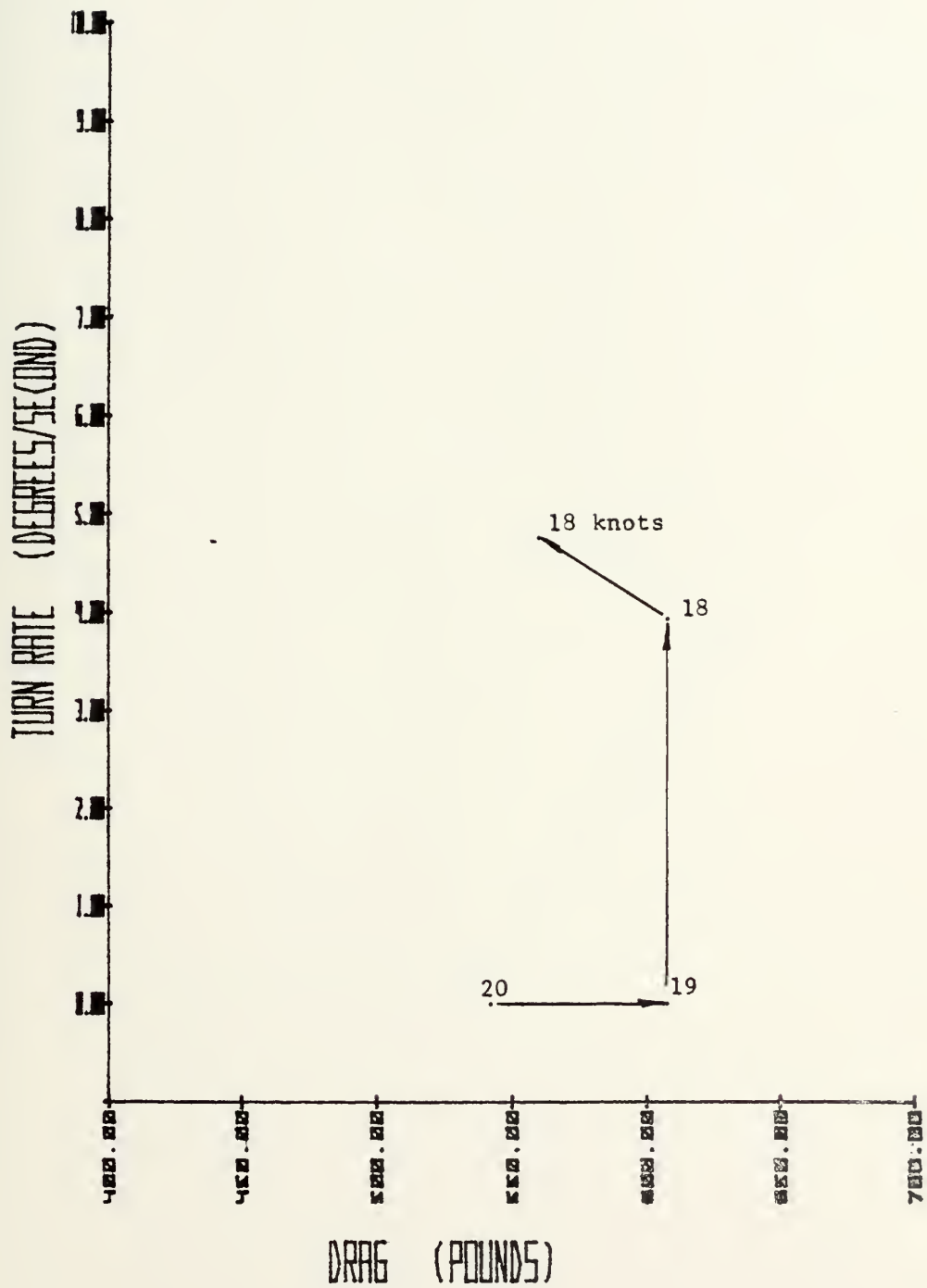


FIGURE 18. LEFT TURN RUNS B 6-9



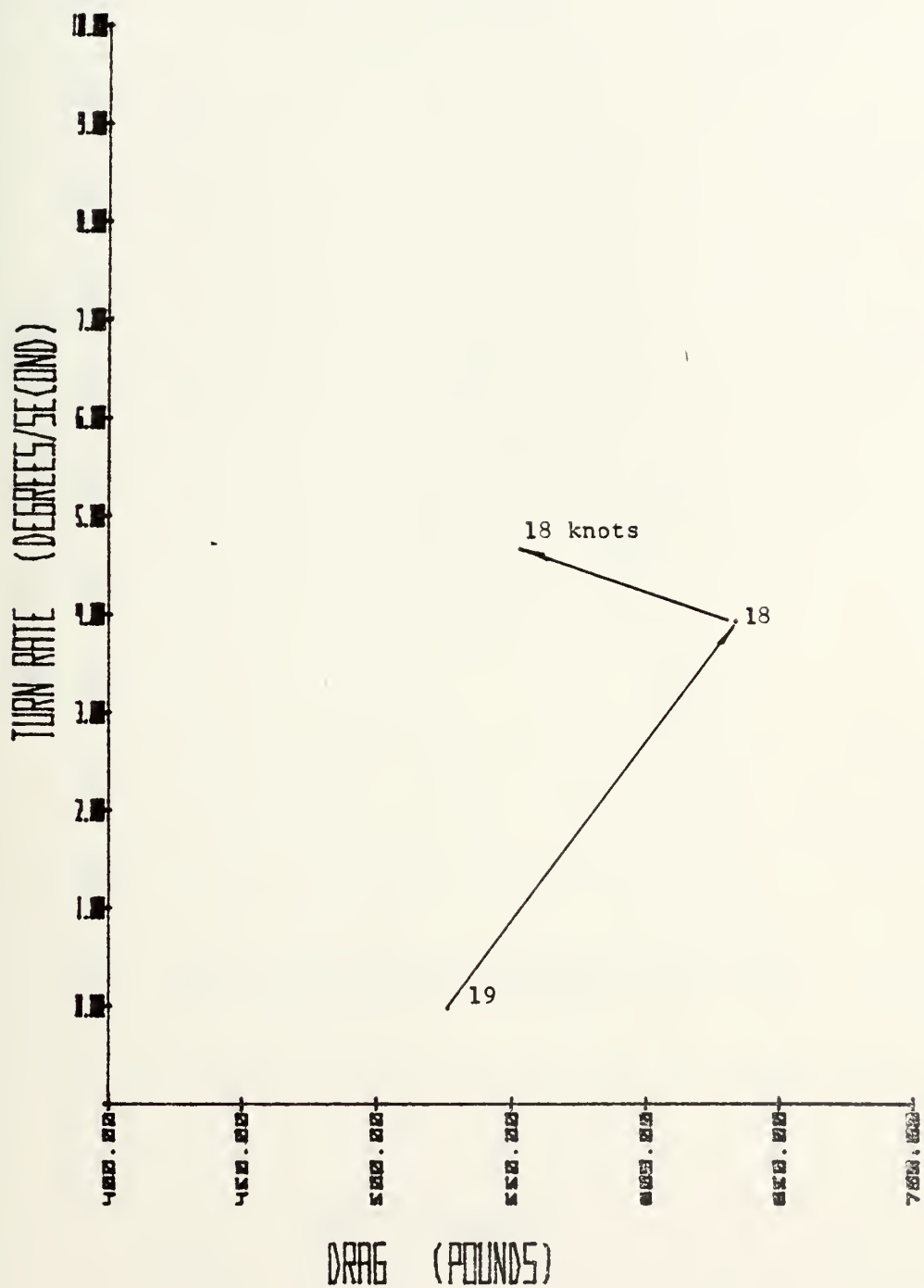


FIGURE 19. LEFT TURN RUNS B 14-16



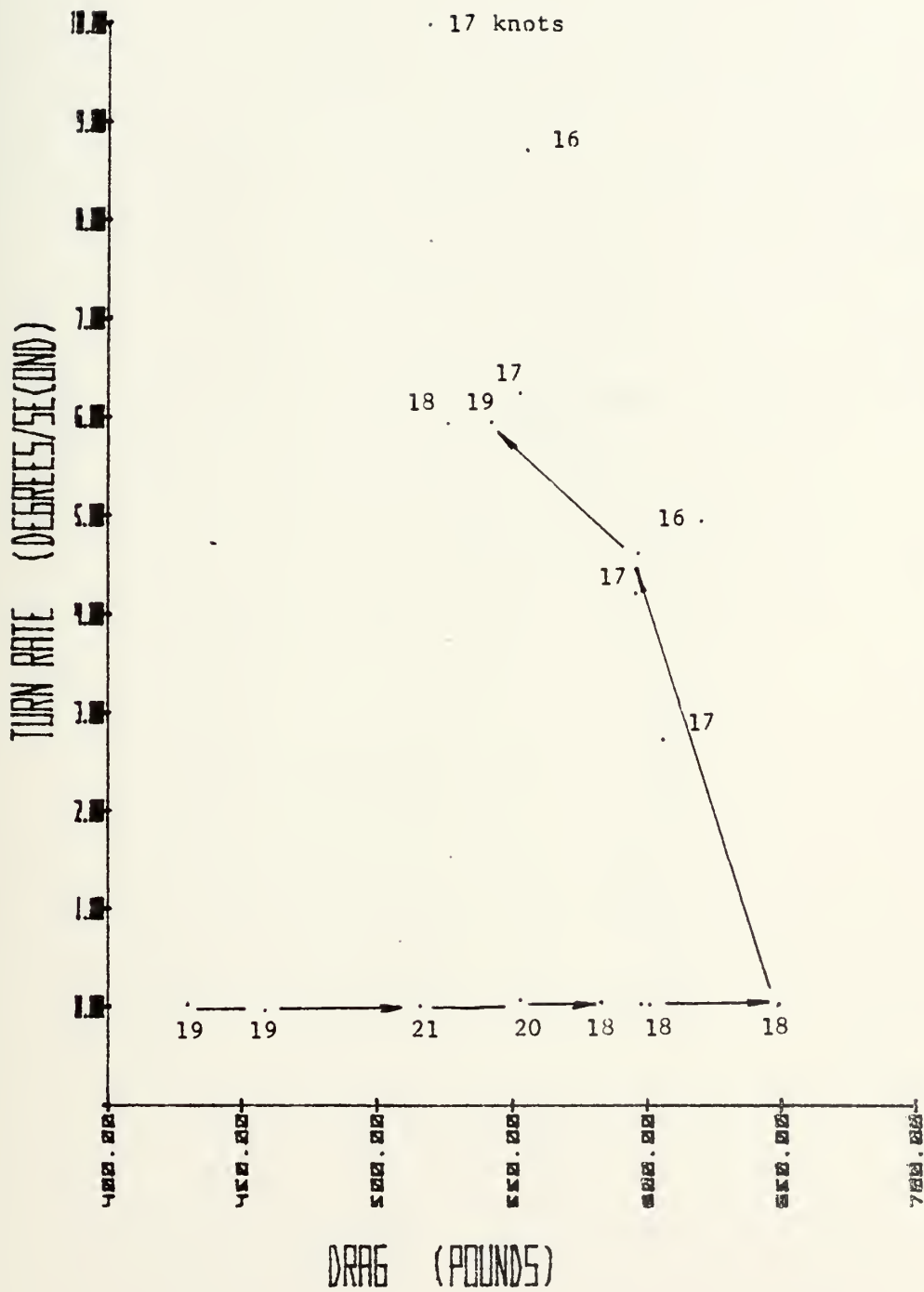


FIGURE 20. COMPOSITE RIGHT TURN PERFORMANCE



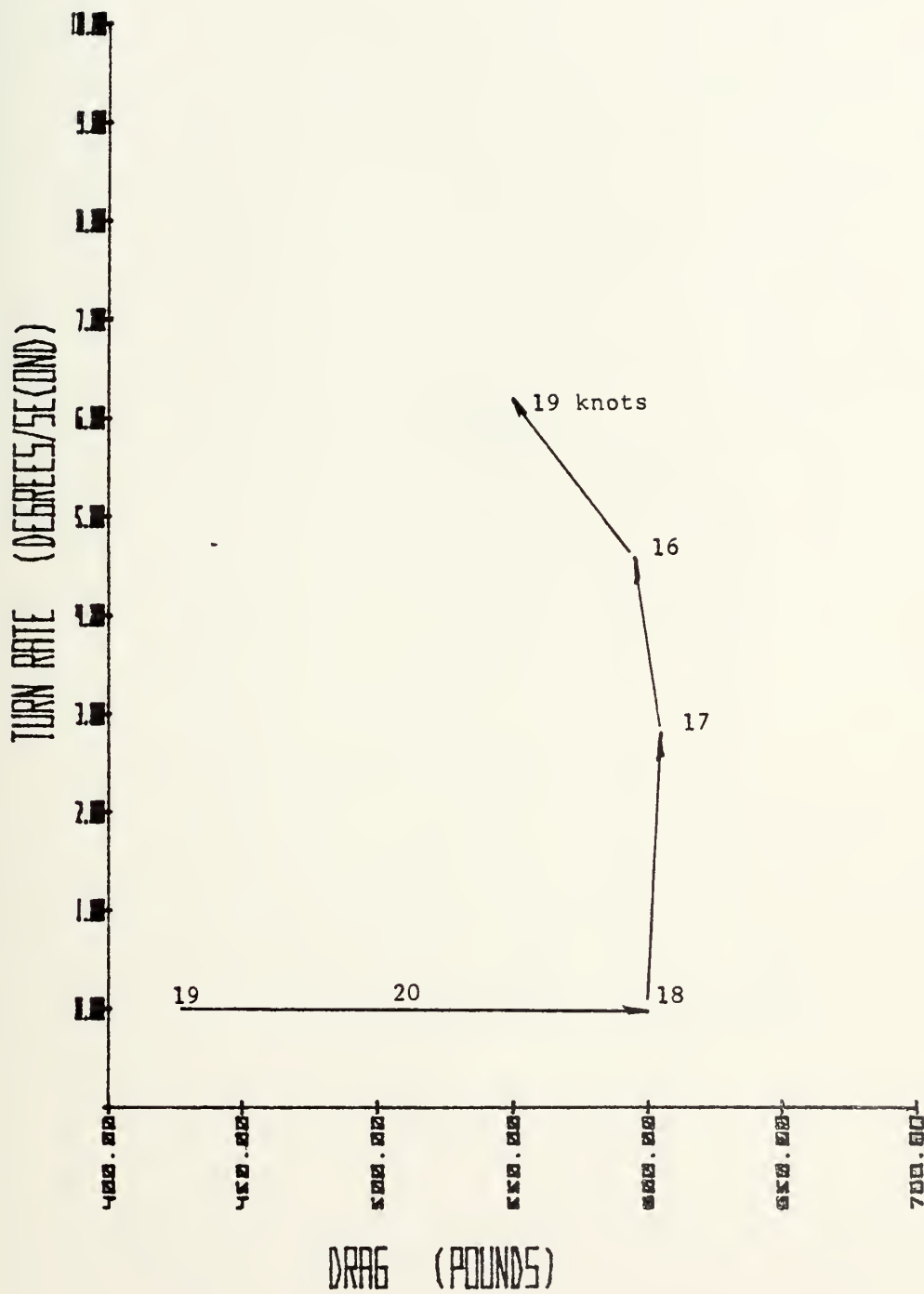


FIGURE 21. RIGHT TURN RUNS B 1-5



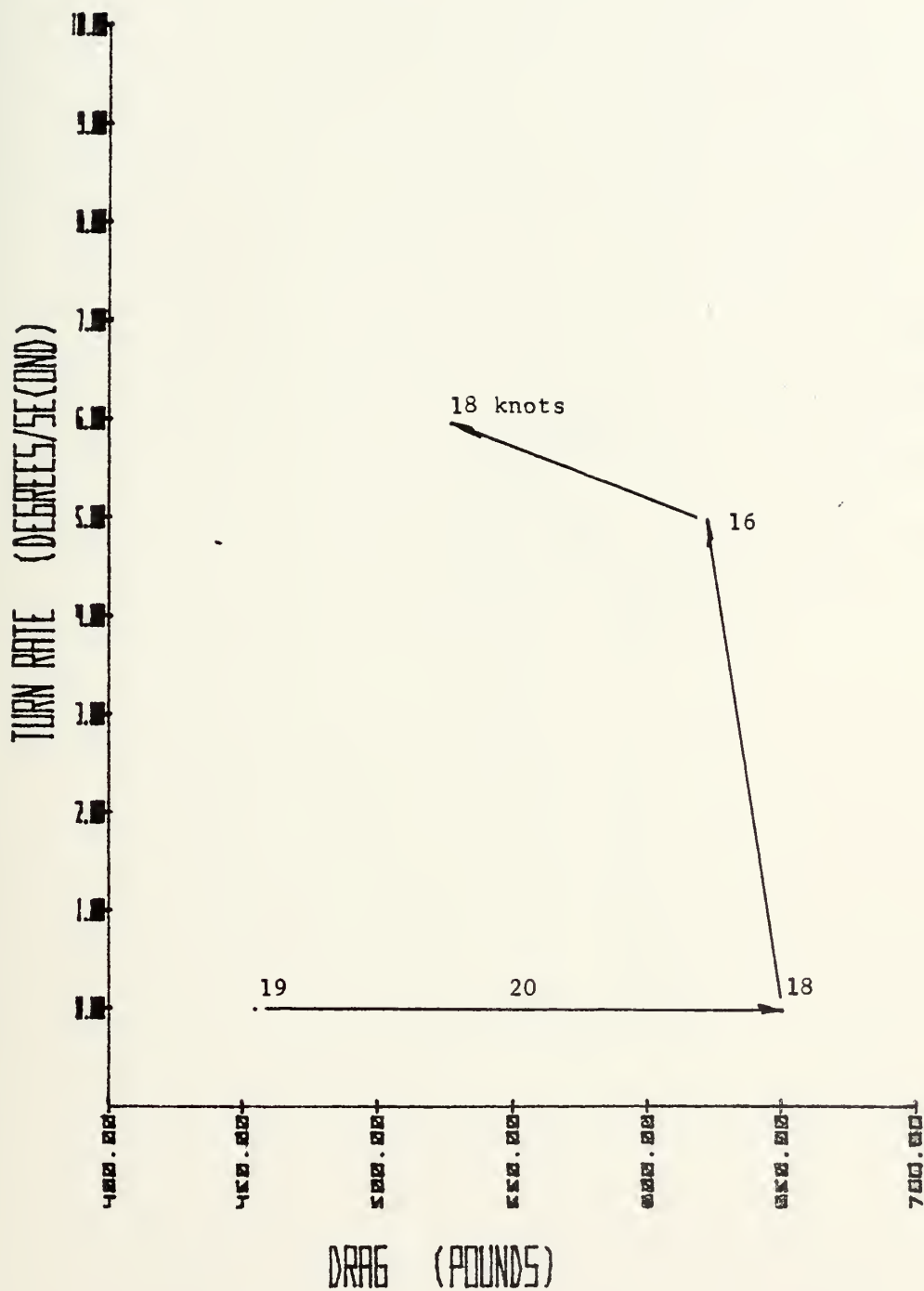


FIGURE 22. RIGHT TURN RUNS B 10-13



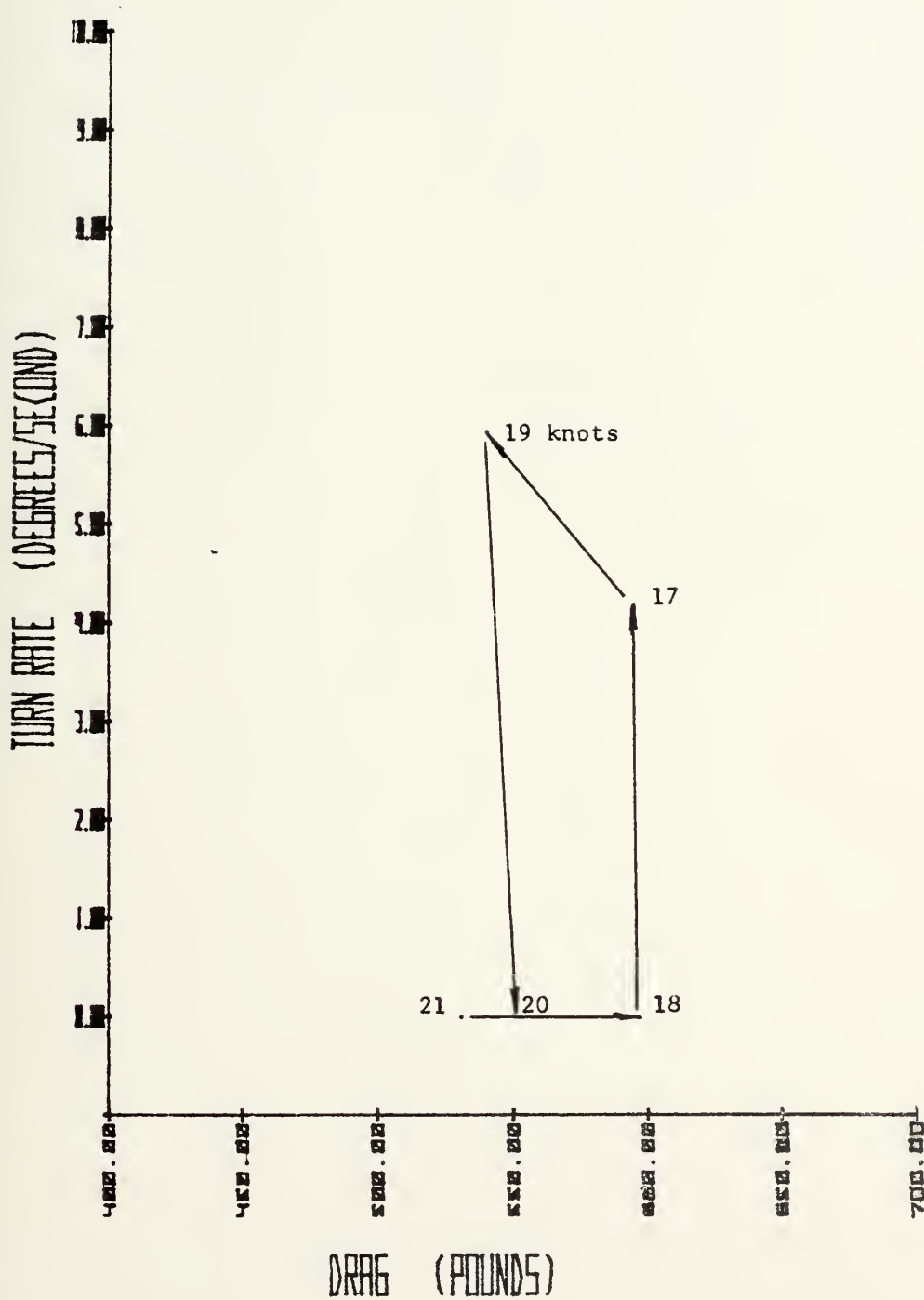


FIGURE 23. RIGHT TURN RUNS A 10-14



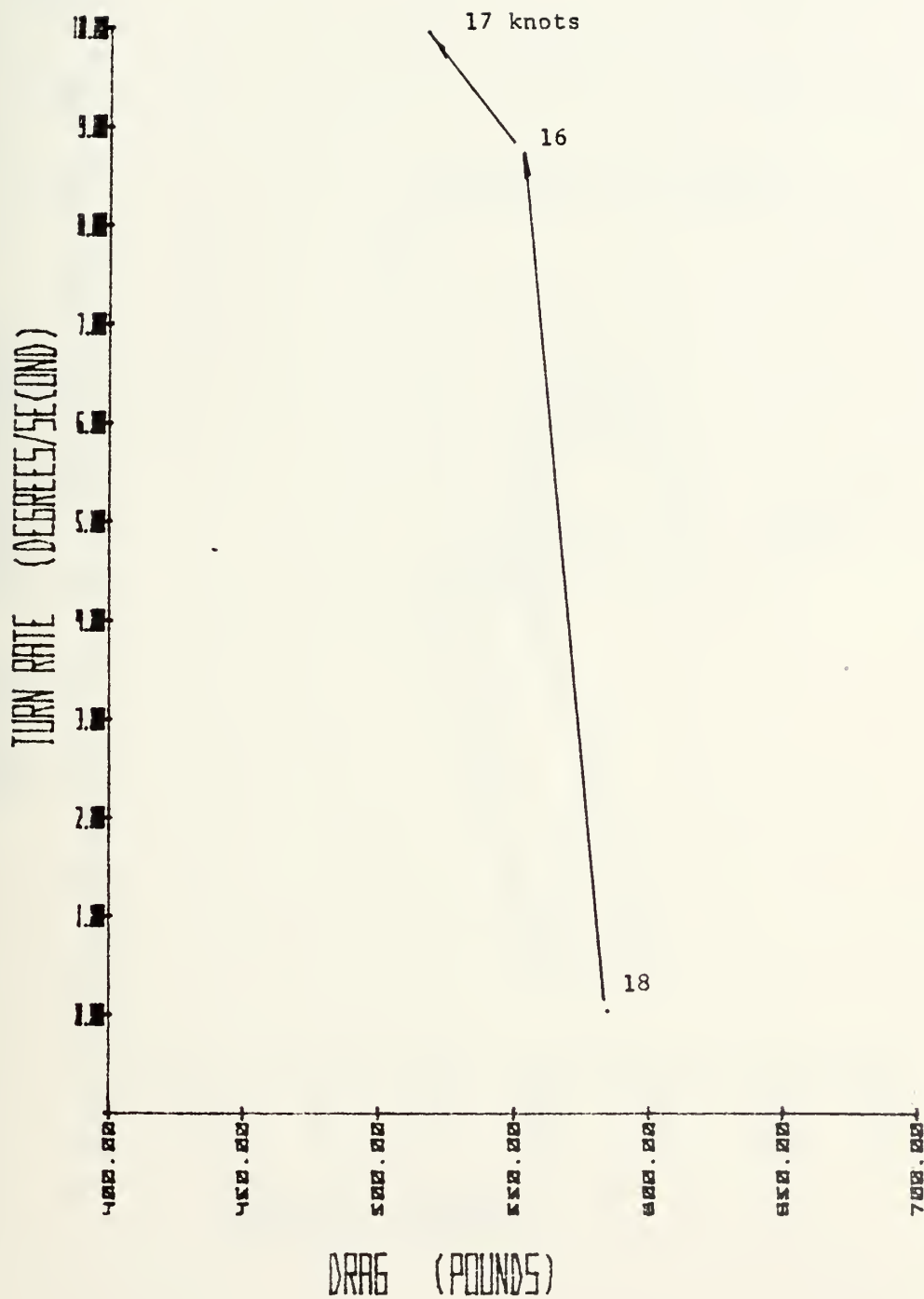


FIGURE 24. RIGHT TURN RUNS A 15-17



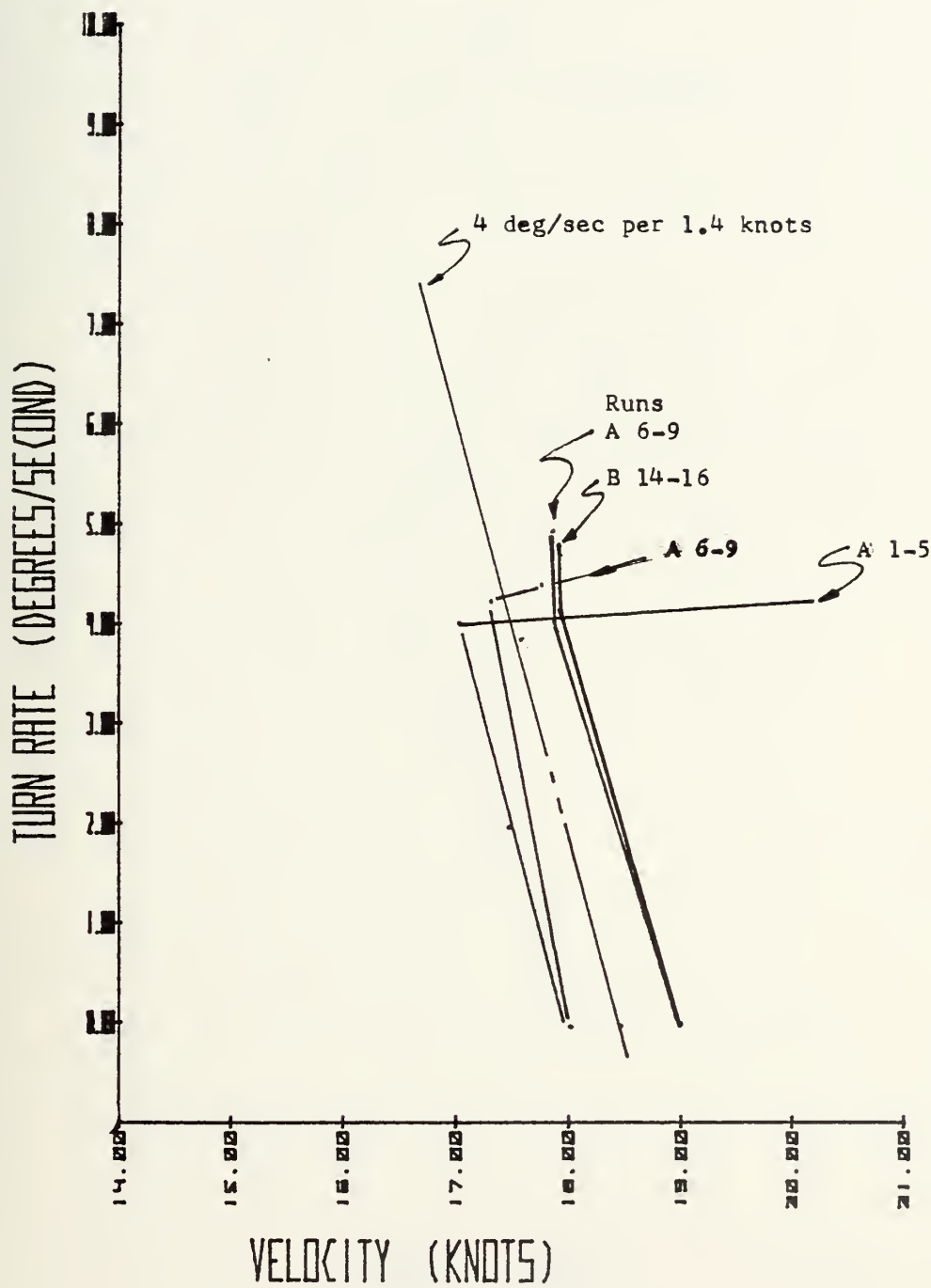


FIGURE 25. LEFT TURN RATE VERSUS VELOCITY



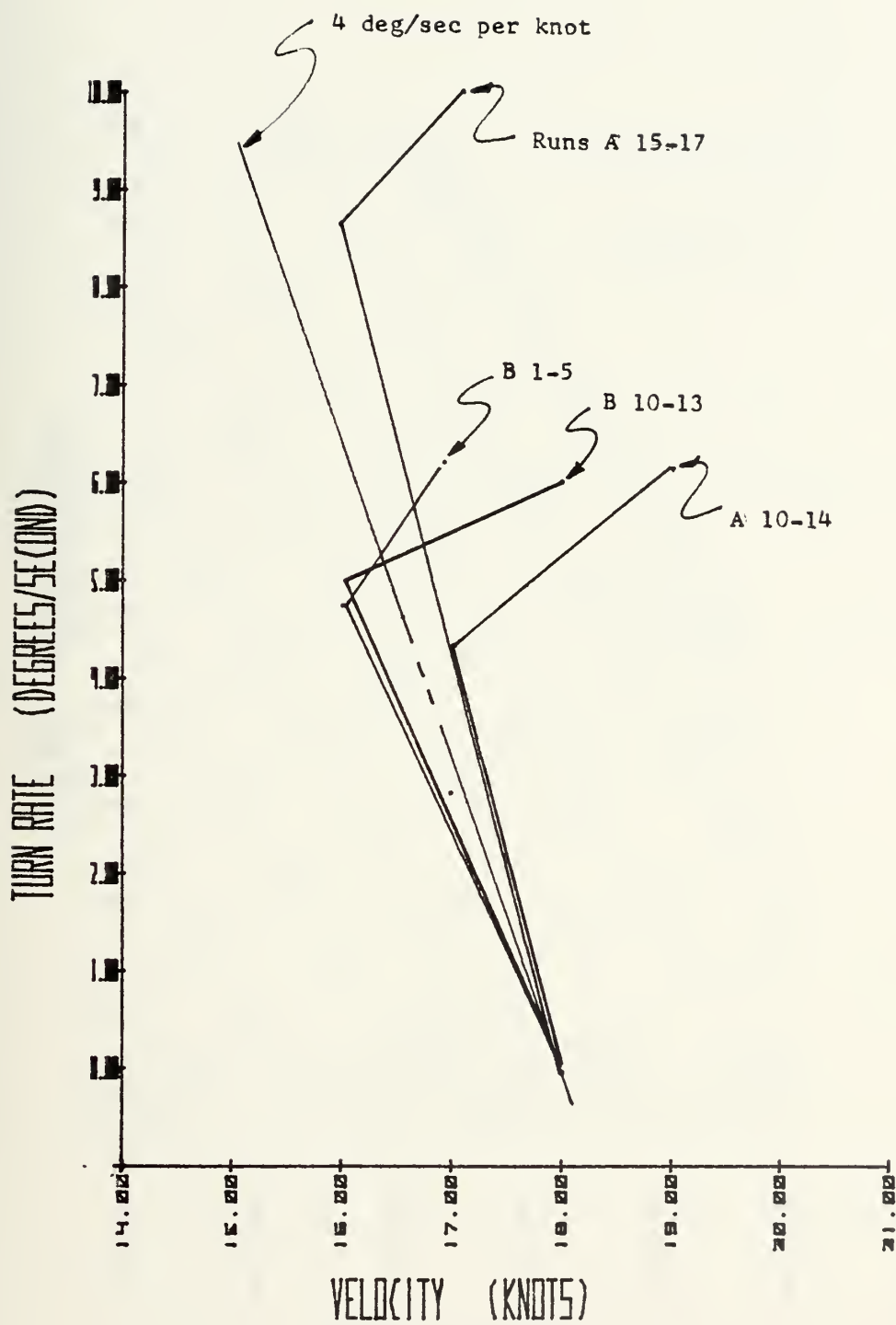


FIGURE 26. RIGHT TURN RATE VERSUS VELOCITY



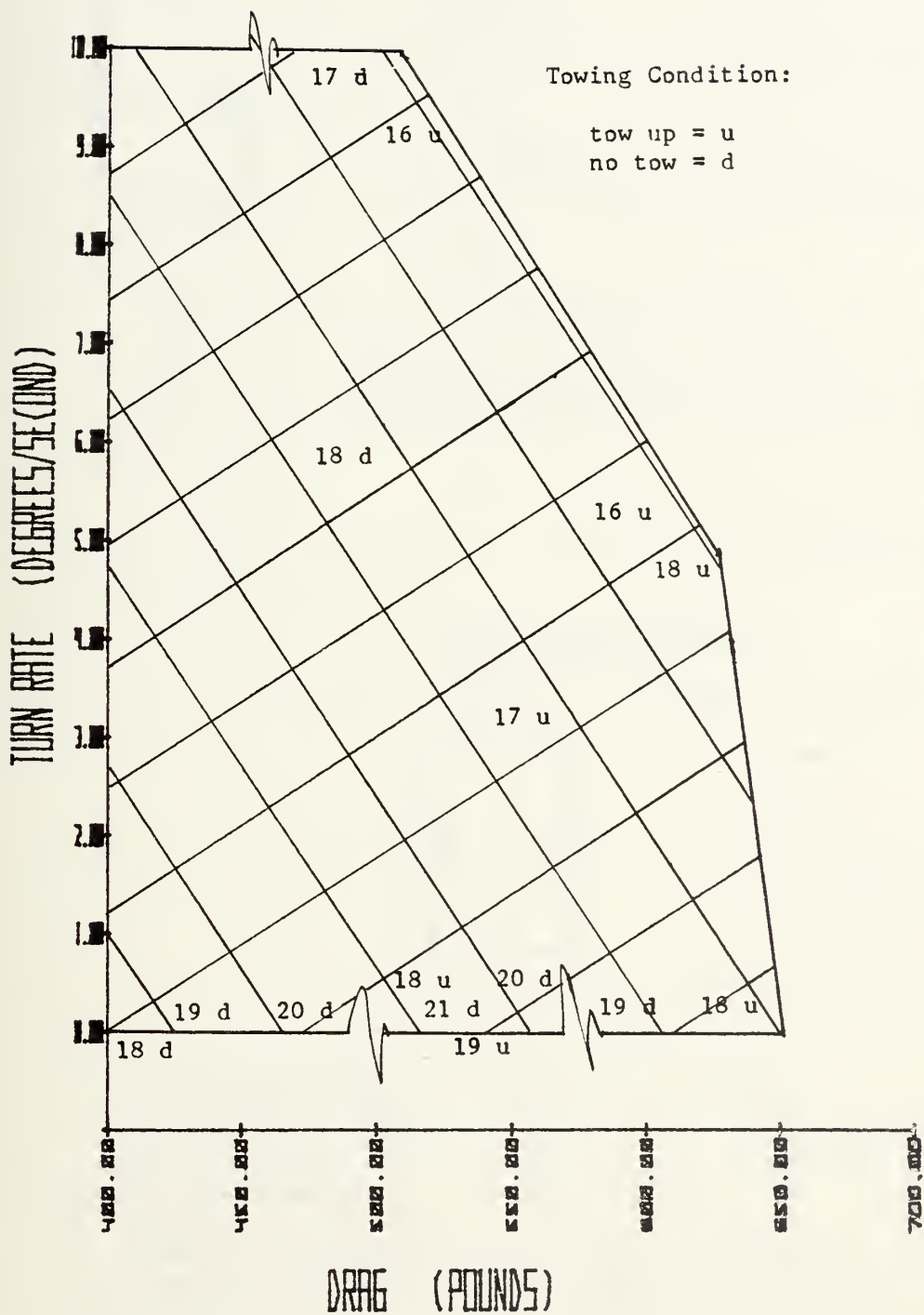
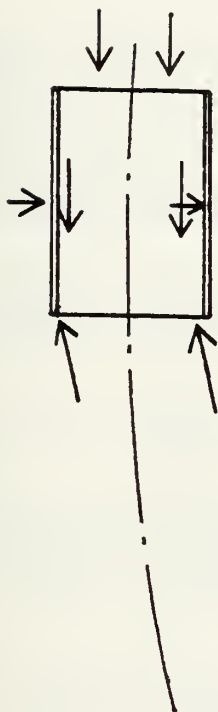


FIGURE 27. DRAG - TURN RATE ENVELOPE



### NON-TOWING TURN PERFORMANCE

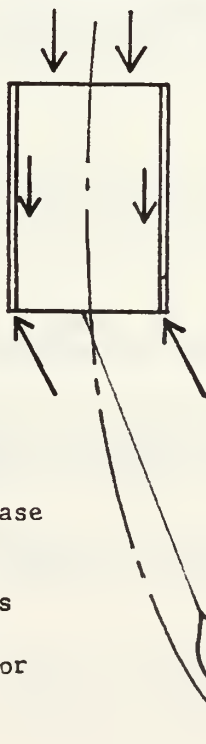


#### LOADS:

1. Sidewalls
  - a. aft
  - b. to outside of turns
2. Thrust
  - a. forward
  - b. to outside of turns
3. Seals
  - a. aft
  - b. athwartship in turns

Turn rate increases 1 degree per second as velocity is decreased 0.5 knots.

### TOWING TURN PERFORMANCE



#### LOADS:

1. Sidewalls
  - a. aft
2. Thrust
  - a. Forward
  - b. to outside of turn
3. Seal
  - a. aft
4. Tow
  - a. aft
  - b. to inside of turn

Turn rate increases 1 degree per second for a velocity decrease of 0.35 knots.

Turn performance is increased due to less sidewall loading and more excess thrust for velocity.

towed boat

FIGURE 28. XR-3 Tow Load Conclusions



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c.1 XR-3 turn performance  
while towing.

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